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Stagnating CO_2 emissions with in-depth socioeconomic transition in Beijing

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HIGHLIGHTS

- The turning point of Beijing's production-based CO_2 emissions arrived in 2007.
- CO_2 emissions declined in industry due to its further transferring and transition.
- Upgradation of internal structure in services promoted the CO_2 emissions peak.
- Consumption composition change in services reduced emissions with urbanization.
- Beijing's experience of peaking CO_2 emissions guides other cities in developing countries.

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ABSTRACT

Curbing the growth of global CO_2 emissions and limiting global average temperature rise to well below 2 °C are important targets for the international society after the Paris Climate Change Conference. Given the continuously increasing emission trends in most of the developing world, peaking emissions as soon as possible during the developing and transition process is a key challenge in realizing the target globally. In this study, we established a comprehensive analysis framework for peaking stage analysis, based on three scopes accounting, and estimating the impact of in-depth socioeconomic transitions on peaking stages. We further applied it to Beijing, which reversed its growth trend in CO_2 emissions and acted as a pioneer in fulfilling the peaking target of emissions during in-depth socioeconomic transition period, in recent years. We found that the turning point for production-based CO_2 emissions in Beijing appeared around 2007, which stopped growing and has since been fluctuating around 100 Mt. During the in-depth industrialization process, accelerating the elimination of energy and carbon intensive industries, such as resource-related heavy manufacturing, promoting the transition from industries to services, and upgrading the internal structure of industries, were key factors determining the CO_2 emissions peak in Beijing. Meanwhile, the optimization of the internal production structure of consumer and producer services also led to a declining trend of services with the in-depth industrial transition. During the in-depth urbanization process, the reduced CO_2 intensity and optimized production structure of shelter and household equipment, and upgraded services dominated consumption structure were the main reasons for urban household CO_2 mitigation. Clarifying the mechanism of the CO_2 emissions peak during the in-depth socioeconomic transition period in Beijing will help us understand the challenges of peak better and provide valuable references for other countries and regions in the developing world that are facing peaking emissions challenges in the processes of their development.

1. Introduction

Curbing the growing trend of the global CO_2 emissions to limit the global average temperature rise to well below 2 °C has become an urgent task, especially after the Paris Climate Change Conference [1]. In recent years, most of the increase of the global CO_2 emissions has come from the developing world [2]. Peaking emissions from the developing world is an essential and critical step in reaching the target globally.

A majority of developing countries is experiencing a period of significant socioeconomic transition, which is featured by transitions in both production and consumption patterns, with industrialization and urbanization, in the process of economic development during the last

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few decades. Such profound socioeconomic transition brings both serious challenges and opportunities for peaking their CO_2 emissions. In particular, understanding how such socioeconomic transitions can impact peaking CO_2 emissions would be an essential step in creating mitigation policies in the developing world.

Peaking CO_2 emissions has aroused the interest of many researchers, given its significant impacts on climate change mitigation. Numerous studies have concentrated on predicting the time or volume of emissions peak by setting up different assumptions. Macroscopically, at the national or regional scale, many researchers have analyzed the emission peak from the perspective of socioeconomic driving factors. Mi et al. [3] suggested that by reducing the annual GDP growth rate to less than 4.5% and decreasing the energy and carbon intensity levels by 43% and 45%, respectively, China's carbon emissions can reach the peak at 11.20 Gt in 2026. Wu et al. [4] investigated the relationship between Qingdao's CO_2 emissions peak and the different driving factors based on a scenarios analysis, and pointed out that controlling the population scale, maintaining economic growth, and raising the rate of urbanization and the proportion of the tertiary industry's added value in GDP, can accelerate the emissions peak. Similar studies on China's emissions peak from the perspective of socioeconomic driving factors can also be found in Yuan et al. [5], Xu et al. [6], Tian et al. [7], and Li et al. [8]. Additionally, Korppoo and Kokorin [9] explored how difficult it was for Russia to achieve its 2020 GHG emissions target and found that the decrease in the economic growth rate may largely help Russia fulfill its emissions reduction promise. Layton and Shahiduzzaman assessed the challenge of achieving emissions targets in Australia [10] and the United States [11] from the view of economic structural changes, welfare effects, population growth, energy consumption, and energy efficiency, based on the Logarithmic Mean Divisia Index (LMDI) method.

Further, considering that energy consumption is the major contributor of CO_2 emissions [12], some researchers have investigated how changes in energy consumption levels and structures have influenced the emission peak, or have predicted the emissions peak through an investigation of energy consumption trends and peaks. Specifically, Jackson et al. [13] reported the stagnation of the global CO_2 emissions growth since 2014, and have attributed the recent trend to the reduction in China's coal use and weaker growth trends in petroleum consumption and the expanding use of renewable energy. Zhou at al. [14] revealed that slower annual growth rate of energy demand and energy efficiency improvement played important roles in promoting a lower emissions trajectory and meeting the 2020 carbon mitigation goals. Meanwhile, an analysis of the emissions peak from the energy consumption and energy structure transition can also be found in Zhang et al. [15] and Den Elzen et al. [16]. In addition, from the perspective of energy peaks, Liu et al. [17] conducted a high-level assessment of China's energy revolution strategy into 2030, and pointed out that it cannot deliver CO_2 peaks earlier than 2030. Zhang et al. [18] showed that a turning point in energy consumption did exist in 2012, and then they further analyzed the energy transition process from the perspective of socioeconomic driving factors. Duan et al. [19] predicted the energy consumption peak and emissions peak simultaneously, and pointed out that China may not deliberately increase CO_2 emissions rapidly for the emission peak to reach as high as possible. Otherwise, it may be difficult to achieve the non-fossil energy target.

Moreover, with a more detailed consideration of the emissions peak, many scholars have worked on predicting the emissions peak at a sectoral scale. Ruijvena et al. [20] explored the future CO_2 emissions from the global steel and cement industries and predicted that the emissions will peak at around 2020–2030 and indicated that it would decrease below the 2010 levels in 2050. Ali at al. [21] studied the CO_2 emissions from the electricity generation sector in Singapore based on an Energy Plan optimization model, and suggested that the 2020 emissions reduction target can be achieved easily due to current natural gas dominated fuel structure strategy, and increasing renewable energy share. Additionally, an analysis on the peaking CO_2 emissions generated in the civil aviation, building sector, and textile industries can be found in Zhou et al. [22], Xiao et al. [23], and Zhao et al. [24], respectively.

Many past studies have predicted the time or volume of CO_2 emissions peak, most of which have focused on prediction based on diversified assumptions. However, there is still no investigation based on real cases that realized the peaking targets in the developing world. Moreover, though there are many studies that focus on the emissions peak from the perspective of socioeconomic driving factors or energy consumption level and structure, the manner in which in-depth socioeconomic transitions, which are currently going on in the developing world, impacts CO_2 emissions peak, is not investigated much. The underlying mechanism remains largely elusive.

Here, we take Beijing, China's leading city in terms of in-depth socioeconomic transitions and CO_2 emission peak, as an empirical case to assess the impact of in-depth socioeconomic transitions on peaking CO_2 emissions quantitatively, as well as to investigate the underlying mechanism. We build up a comprehensive analysis framework for peaking stage analysis, based on three scopes accounting, and further explore how the in-depth socioeconomic transition impacts the peaking of CO_2 emissions.

Beijing is a representative region that has experienced in-depth socioeconomic transition in the past few decades. Services in Beijing contributed to more than 80% of the GDP by 2016 (Fig. A1 in the Appendix), and services have been the pillar industry since 1995, with the share of the secondary industry declining in Beijing's economic structure (Fig. A2 in the Appendix). Beijing's industries experienced a further upgradation of their internal structures. The strategies of emerging industries were vigorously developed, and the quality of producer services has been improving continuously [25]. Additionally, at the top level of urbanization nationwide, Beijing's rate of urbanization exceeds 80%, second only to Shanghai in China (Fig. A3 in the Appendix). Moreover, Beijing has introduced a very intensive mitigation policy in recent years, which presents ways in which CO_2 emissions can be peaked against rapid economic growth and in-depth socioeconomic transitions. Specifically, energy reform was promoted actively, such as through the "reduction of coal consumption and development of new energy and renewable energy" [26]. The last but not the least, Beijing is one of the largest cities in the world. Considering that cities are the center of life and production and have induced most of CO_2 emissions in the world [27], Beijing also offers a good example for other developing metropolises on ways to mitigate CO_2 emissions. Elucidating how Beijing realized a cessation in the growth of CO_2 emissions with an in-depth socioeconomic transition, will help understand the challenges of peaking emissions better and provide valuable information based on experience for other regions and countries.

We improved previous studies in the following points. First, we selected Beijing, the leading city in peak emissions among developing countries, as a real case to investigate issues pertaining to emissions peak, which was found lacking in past studies, considering that only very few cities show signs of having reached the peak of CO_2 emissions in recent years. Second, we noticed the trend of in-depth socioeconomic transition, which is positioned as an important strategy in the socioeconomic development policy system of developing countries in recent years. To the best of our knowledge, this is the first time that a study explores the mechanism of peaking CO_2 emissions from the perspective of an in-depth socioeconomic transition in the developing world. Thirdly, we built up a comprehensive analysis framework for peaking stage analysis, based on the three scopes accounting, and qualifying the impacts of in-depth socioeconomic transition on emissions peak, given the fact that researchers in the past have rarely considered the three different accounting methods simultaneously, and there is still no method for comprehensive analysis to qualify the in-depth socioeconomic transition.

The remainder of this paper is organized as follows. In Section 2, we introduce the analysis framework, methodology, and data preparation.

Section 3 shows the results of the overall trends in CO_2 emissions with three scopes, and the sources of production-based CO_2 emissions in Beijing. Then, the effects of in-depth industrialization and urbanization processes on the CO_2 emissions peak, are presented. In Section 4, we discuss the mechanism of the in-depth socioeconomic transitions reversing Beijing's CO_2 emissions, and the challenges of peaking CO_2 emissions in the future. Furthermore, the experience of CO_2 emissions mitigation from Beijing is listed. Section 5 concludes the paper.

2. Methodology and data

2.1. Analysis framework

As there are different emissions accounting methods, the peaking stages also vary accordingly. Here, we present three typical scopes of emissions namely:

- Production-based CO_2 emissions (Scope 1): It covers all the direct CO_2 emissions from domestic production within its boundaries.
- Production-based emissions and electricity induced emissions (Scope 2): It combines the CO_2 emissions embodied in the purchased electricity with production-based CO_2 emissions.
- Consumption-based emissions (Scope 3): It includes all the emissions caused by local final consumption, no matter where the CO_2 emissions are generated [28].

To evaluate the impact of in-depth socioeconomic transitions on peaking stages, we include two essential steps in the framework (Fig. 1).

First, transitions effect from the perspectives of two general sources, namely, final demand categories and socioeconomic driving factors.

Second, as the evaluation of general sources is still rough, we selected six specific parameters to further quantify the effects of the in-depth socioeconomic transition process. To quantify the effects of the in-depth industrialization process, we have the four following parameters:

- **Overall structure,** which presents a sectoral contribution to CO_2 emissions in the entire economic structure, and indicates the significance of each sector in the economic system in terms of CO_2 emissions. This means that pillar industries usually have higher proportions in the overall emissions structure. To some degree, changes in the overall structure reflect the industrial transition.
- **Trading structure,** which indicates emissions flows with trading, which can reflect the competitive advantages of industries in the economy. Generally, the higher the share that industries occupy in the export structure, the more competitive they are. Meanwhile, industrial transfer trends can be reflected from the change in trading structures. The growing trend in the export structure reflects the "flow in" of the sector and increasing trend in import structure reflects the "flow out" of the sector [29].
- **Production structure**, which indicates the internal input structure by depicting the relationship between one sector and its upstream sectors. Changes in the production structure represent the changes in the industrial internal structure, which is related to the technology level and organization efficiency in the production process of the products [29].
- **Investment structure in industrial sectors** reveals the demand and prospects of industrial sectors in the economic structure. Investment structure is usually consistent with the demand structure in a period of rapid socioeconomic transition. In addition, by transferring investment to several key sectors, the investment structure changes, reflecting the direction of industrial structure adjustment.

For the evaluation of in-depth urbanization effects, the two parameters are:

- **Urban household consumption**, which includes consumption level and consumption composition. The former depicts the changes in consumption scale with the migration of population from rural to urban areas, and household expenditure with residents' income rising. The latter reflects transitions in the residents' lifestyle and consumption patterns in the process of urbanization [30].
- **Investment in building and infrastructure** indicates the demand in building and infrastructure construction [31]. In the rapid process of urbanization expansion, investment in building and infrastructure varies significantly, in order to fulfill increasing demand.

The six key parameters mentioned above can be estimated based on the Input-output (IO) analysis and the Structural Decomposition Analysis (SDA) method, which are described in detail in the following sections.

2.2. Methodology

2.2.1. Basic input-output (IO) model

IO analysis is a widely accepted method that helps understand interdependent relationships among multiple sectors and depicts features of the socioeconomic system [32]. The basic row balance IO table is

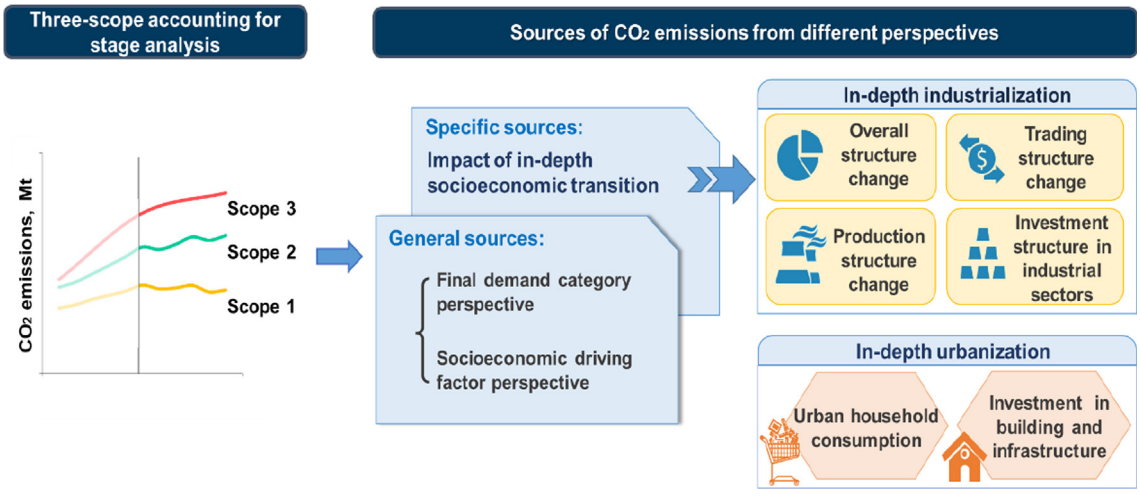

Fig. 1. Framework for peaking stage analysis and impacts of in-depth socioeconomic transition on the CO_2 emissions peak.

expressed as:

$$x_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{1}$$

where x_i denotes the total output of sector i; z_{ij} means monetary flows from sector i to sector j; y_i represents the final demand of sector i, including rural and urban household consumption, government consumption, investment, and export. The direct input coefficient $a_{ij} = \frac{z_{ij}}{x_j}$, that is the input from sector$i$ to sector j when one unit of output is generated in sector j, is introduced to obtain the followed equation:

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + y_i \tag{2}$$

This can be expressed in the form of matrix:

$$X = AX + Y \tag{3}$$

where $A = (a_{ij})$ is the direct input coefficient matrix; X and Y are the vectors of total output and final demand, respectively. Thus, we can further obtain:

$$X = (I-A)^{-1}Y = LY \tag{4}$$

where I stands for identity matrix; $L = (I-A)^{-1}$ is Leontief inverse matrix, which means total output required to meet unit final demand, reflecting the production structure. Considering CO_2 emissions, Eq. (4) can be expanded as:

$$f = FLY \tag{5}$$

where f denotes the sectoral carbon dioxide emissions and F is CO_2 intensity.

2.2.2. Multi-regional input-output (MRIO) model

For MRIO analysis, by adding transactions of intermediate and final demand flows among regions, Eq. (1) can be transformed into [33]:

$$x_i^r = A^{rr}x^r + y^{rr} + \sum_{s\neq r} A^{rs}x^s + \sum_{s\neq r} y^{rs} \tag{6}$$

where x_i^r stands for sector i's total output in region r; x^s is the total output of region s; A^{rr} and A^{rs} represent the direct input coefficient matrix from region r to region r and region s, respectively; y^{rr} and y^{rs} are the final demand flows from region r to region r and region s, respectively. Thus, in a MRIO table with n regions, we can obtain the formula of compound matrices:

$$X^* = A^*X^* + \mathrm{Y}^* \tag{7}$$

where X^*, A^*, and Y^* denote the compound regional total output, direct input coefficient, and final demand matrices, respectively. The following MRIO model is further obtained:

$$X^* = (I-A^*)^{-1}\mathrm{Y}^* = L^*\mathrm{Y}^* \tag{8}$$

where $L^* = \begin{pmatrix} L^{11} & \cdots & L^{1n} \\ \vdots & \ddots & \vdots \\ L^{n1} & \cdots & L^{nn} \end{pmatrix}$, in which the matrix L^{rs} represents the amount of output generated in region r to satisfy a unit final use in region s. Considering CO_2 emissions, the MRIO model can be also expanded as:

$$f^* = F^*L^*\mathrm{Y}^* \tag{9}$$

where $F^* = \begin{pmatrix} F^1 \\ \vdots \\ F^n \end{pmatrix}$ represents compound regional CO_2 emissions intensity.

2.2.3. CO_2 emissions with three scopes

Scope 1 (f_1) is based on two important parts of emissions:

$$f_1 = f_{fuel} + f_{process} \tag{10}$$

where f_{fuel} denotes the emissions caused by direct fossil fuel combustion from all industrial producing sectors, which include all possible producing activities conducted within a region's administrative boundaries. Fossil fuels used as chemical raw materials, as well as the energy loss during transportation, were removed from the total fossil fuel consumption, to avoid double counting [34]. $f_{process}$ means emissions caused by industrial processes. The process-related emissions refer to CO_2 emitted as a result of physical-chemical reactions in the production process, and not the energy combusted by the industry [35]. The fossil fuels used in this transformation stage are considered to be carbon emissions from fossil fuel combustion performed by industrial sectors, and are not considered as industrial process emissions [36]. We assume there are m types of fossil fuel, n sectors, and t industrial processes, f_{fuel} and $f_{process}$ can be calculated by [37]:

$$f_{fuel} = \sum_m \sum_n f_{mn} = \sum_m \sum_n AD_{mn} \times NCV_m \times EF_m \times O_{mn} \tag{11}$$

$$f_{process} = \sum_t f_t = \sum_t AD_t \times EF_t \tag{12}$$

where f_{mn} represents CO_2 emissions generated by fossil fuel m in sector n; AD_{mn} means the consumption of fossil fuel in sector n; NCV_m and EF_m denote net caloric value and emission factor of fossil fuel m, respectively; O_{mn} stands for oxygenation efficiency of fossil fuel m in sector n; f_t, AD_t and EF_t are carbon emissions, production volume, and emission factor from industrial process t, respectively.

Besides Scope 1 emissions, CO_2 emissions caused by purchased electricity, which is an important source of secondary energy and is easy to transport, are included in Scope 2:

$$f_2 = f_1 + f_e \tag{13}$$

f_e is the CO_2 emissions involved in purchased electricity from other regions, and which is different from the direct energy consumption related to CO_2 emissions within its own boundary, as mentioned above like f_{fuel} and $f_{process}$. f_e can be expressed as:

$$f_e = EP \times EF_{rg} \tag{14}$$

where EP represents Beijing's imported electricity from the North China Electricity Grid; EF_{rg} means the emission factor of the grid baseline of the North China Electricity Grid.The consumption-based emissions (Scope 3) of region s can be calculated as:

$$f_3 = \sum F^r L^{rs} y^s + f_h \tag{15}$$

where $\sum F^r L^{rs} y^s$ stands for the indirect emissions embodied in products and services finally consumed by region s, based on the MRIO model (see Eqs. (6)–(9)). f_h refers to direct CO_2 emissions from household consumption of region s.

Specifically, for Beijing, we first used China's MRIO tables to calculate Beijing's consumption-based emissions within China, and further used Eora MRIO tables to calculate sectoral CO_2 emissions embodied in China's international imports, and estimated the sectoral CO_2 emissions embodied in Beijing's international import by proportions.

2.2.4. Structural Decomposition Analysis (SDA)

SDA is commonly used to calculate respective variations of several factors during a period [38,39]. Based on Eq. (5), we can decompose the final demand vector y into three factors:

$$f = FLy = FLy_c y_l p \tag{16}$$

where $y_c = \frac{y_i}{\sum y_i}$ is the final demand composition, that is, the proportion of each sector in the final demand; y_l refers to the final demand level, that is the per capita final demand, reflecting the economic development level; and p is the total population. In addition, given two sources of CO_2 emissions, the emissions caused by fossil fuel combustion (f_{fuel}) or industrial process ($f_{process}$) can be decomposed respectively, as:

$$f_{fuel} = F_{fuel} Ly = \varepsilon E_s E_i L y_c y_l p \quad (17)$$

$$f_{process} = F_{process} Ly = F_{process} L y_c y_l p \quad (18)$$

Similarly, CO_2 emissions related to urban household consumption (f_{urb}) can be expressed as:

$$f_{urb} = F L y_{urb} = F L y_{urb.c} y_{urb.l} up \quad (19)$$

where ε is the emission coefficient; E_s represents the energy structure; E_i is the energy intensity; $F_{process}$ represents the CO_2 intensity from production process; $y_{urb.c}$ represents the production structure of urban household consumption; $y_{urb.l}$ is per capita urban household consumption level; and u is the urbanization rate, that is the share of the urban population in the total population.

Based on SDA, the decomposition of Eq. (16) can be expressed as follows:

$$\Delta f = \Delta F L y_c y_l p + F \Delta L y_c y_l p + F L \Delta y_c y_l p + F L y_c \Delta y_l p + F L y_c y_l \Delta p \quad (20)$$

where Δf refers to the total CO_2 emission changes in a given period; ΔF represents the variation in CO_2 intensity; ΔL indicates changes in the production structure; Δy_c and Δy_l reflect variations in the final demand structure and final demand level, respectively; and Δp depicts the total population changes in Beijing.

Eqs. (17)–(19) can be also written in similar ways (see Appendix), which reflect variations in CO_2 emissions caused by fossil fuel combustion, industrial processes and urban household consumption, respectively. Given n factors have $n!$ different decompositions, we calculate the average of all possible results [40].

2.3. Data

In this study, the basic data were IO tables and CO_2 emissions. We obtained seven IOTs for Beijing (1997, 2000, 2002, 2005, 2007, 2010, and 2012) with 42 sectors from Beijing's input and output survey network in 2012. We further aggregated 42 sectors into 35 sectors, in order to realize the match between these IO tables in Beijing (see Table A1 in the Appendix). In addition, given the international and intranational imports used to calculate consumption-based emissions, we obtained MRIO tables (2002) for China from Shi and Zhang [41] and (2007 and 2012) from Mi et al. [42], respectively, and world MRIO tables (2002, 2005, 2007, 2010, and 2012) from the Eora MRIO Dataset [43,44]. In order to avoid the influence of price fluctuations, we obtained price indexes of different sectors from the National and Beijing's Statistical Yearbooks, and converted the IOTs into 2012 constant price using the double deflation method [45].

In this study, two components of the CO_2 emissions are covered. In order to calculate CO_2 emissions generated by fossil fuel combustion, we obtained the energy balance tables (1997–2015) and energy consumption tables (1997–2015) detailing different sectors and different energy types from the National Energy Statistical Yearbook and Beijing's Statistical Yearbooks, respectively. We estimated fossil fuel related CO_2 emissions based on earlier studies [36,46,47]. As for the emissions from the production process, we only include cement here, given the insufficient data from other industrial sectors [47].

3. Results

3.1. Overall trends in CO_2 emissions with three scopes in Beijing

It is interesting to find significant disparities in CO_2 emissions trends in Beijing according to three scopes (Fig. 2). The turning point of the production-based CO_2 emissions (Scope 1) occurred in 2007. Before 2007, production-based CO_2 emissions in Beijing exhibited a continuous rise, with an average annual growth rate of 5.5%. After 2007, it showed a somewhat undulating pattern that fluctuated around 100 Mt. Considering the CO_2 emissions attributed to importing electricity

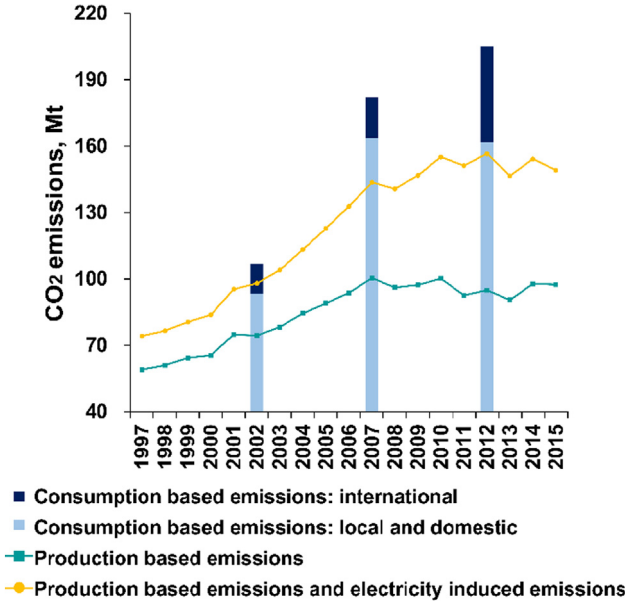

Fig. 2. Variations in CO_2 emissions from three scopes in Beijing during 1997–2015.

(Scope 2), the turning point arrived slightly later in 2010. The gap, reflecting the CO_2 emissions related to purchased electricity, had been gradually expanding since 2007, but the expansion stopped after 2010. In contrast to the relatively stable trends for both Scope 1 and Scope 2 emissions, consumption-based CO_2 emissions (Scope 3) showed an upward trend between 2002 and 2012, with an average annual growth rate of 6%. In short, the direct CO_2 emissions generated by local economic activities and CO_2 emissions attributable to electricity purchased from other regions have stopped growing in recent years, whereas the CO_2 emissions caused by local consumption, including the direct CO_2 emissions and those embodied in imported products and services exhibit a continuously rising trend.

3.2. Sources of production-based CO_2 emissions in Beijing

As production-based CO_2 emission is considered to be a typical indicator of regional carbon emissions management in China and internationally [48], we focus on the sources of production-based CO_2 emissions in the following analysis.

3.2.1. Direct sources of CO_2 emissions

Among all sources, CO_2 emissions reductions in the industrial sectors was the main reason for the turning point in production-based CO_2 emissions in 2007 (Fig. 3a). Specifically, industry, as the largest source of direct CO_2 emissions, was experiencing increasing CO_2 emissions at an average annual rate of 2.7% (13.9 Mt increment) during the period of 1997–2007. However, both the share and volume of CO_2 emissions in industrial sectors showed a continuously decreasing trend during the 2007–2015 period, varying from 59.3% (59.6Mt) to 38% (37.6 Mt), at an average annual declining rate of 5%. Compared with the rapid decline in the industrial sectors after 2007, CO_2 emissions in services, transport and storage, and urban household consumption exhibited completely different trends since then. Services accounted for the second largest source of the production-based emissions structure during 1997–2007, which was at an average annual growth rate of 16.3%, accounting for an increment of 6.8 Mt in CO_2 emissions. Since 2007, CO_2 emissions related to services showed great fluctuations. Transport and storage replaced services as the second major source after 2007, and maintained a steady growth during 1997–2012, at an average annual growth rate of 12.6% (25.7 Mt increment).

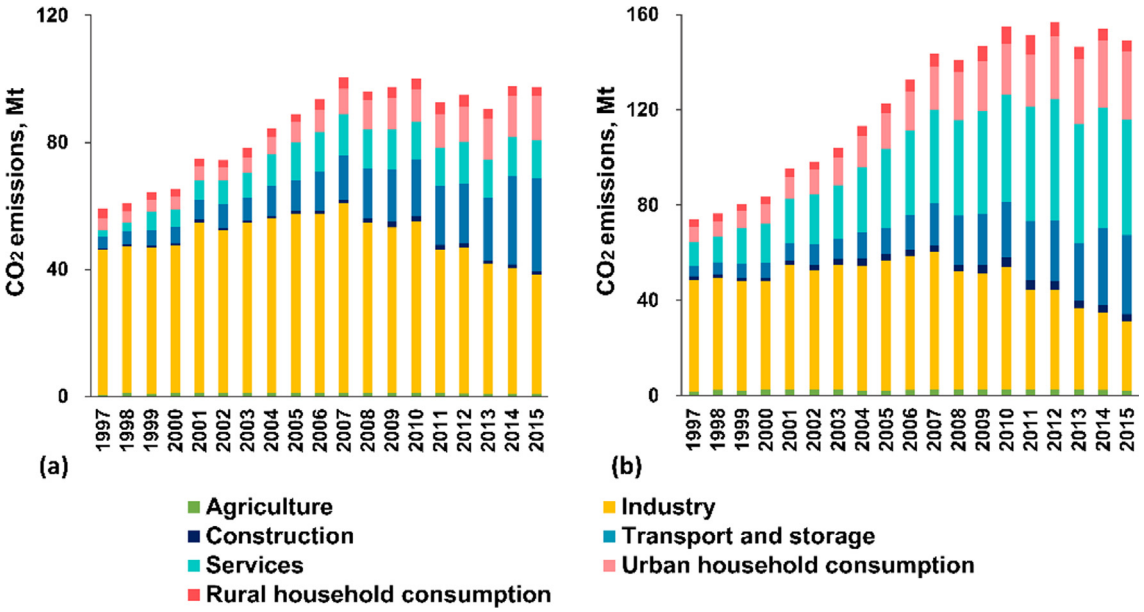

Fig. 3. Variation in the structure of production-based emissions in Beijing, 1997–2015: (a) direct sources of CO_2 emissions structure; and (b) CO_2 emissions structure including those embodied in imported electricity.

Additionally, CO_2 emissions caused by urban household consumption exhibited a trend of rising continuously during 1997–2015, accounting for a 26.4% increment (10.1 Mt) in CO_2 emissions, while the average annual growth rate during 1997–2007 (7.9%) was faster than that during 2007–2015 (5.2%).

Considering CO_2 emissions related to purchased electricity, we found a similar general pattern, with several small differences (Fig. 3b). Firstly, the services surpassed industrial sectors and became the top contributor of CO_2 emissions since 2011, indicating a much stronger contribution from services while considering the impact of electricity consumption. Secondly, CO_2 emissions from urban household consumption was also enlarged significantly while considering imported electricity, which reflects a large amount of electricity consumed by urban households. Thirdly, almost all the sectors maintained steady growth before 2010, and the disparities between the trends of the different sources emerged in 2010. This clarified why the turning point arrived later for imported electricity than for production-based CO_2 emissions.

3.2.2. Analysis from the perspective of final demand categories

From the viewpoint of final demand categories, trade played a dominant role in affecting Beijing's CO_2 emissions (see Fig. 4). Beijing was always a net-importer, which helped avoid 291.4 Mt of CO_2 emissions in the 1997–2012 period. Because the increase in exports is greater than imports, the CO_2 emissions related to net-imports showed a declining trend since 2007. Both imports and exports can be divided into two components, namely, intranational and international trade. CO_2 emissions related to intranational imports/exports occupied a share of 60 to 92% of the total trade during 1997–2012. Particularly in 2010–2012, the amount of CO_2 emissions embodied in intranational imports and exports increased sharply, accounting for 151.4% (203.5 Mt) and 218.8% (279.5 Mt) of increase, respectively.

As for CO_2 emissions associated with investment, based on the turning point in 2007, we can shed light on it in terms of two stages. Before 2007, 123.4% (52.2 Mt) of the CO_2 emissions increment were linked to investment, while after 2007, investment led to 840% (53.9Mt) of CO_2 emissions reduction. The trends of CO_2 emissions related to investment were consistent with total CO_2 emissions. In addition, CO_2 emissions related to government consumption and urban household consumption also showed the same trends with the total

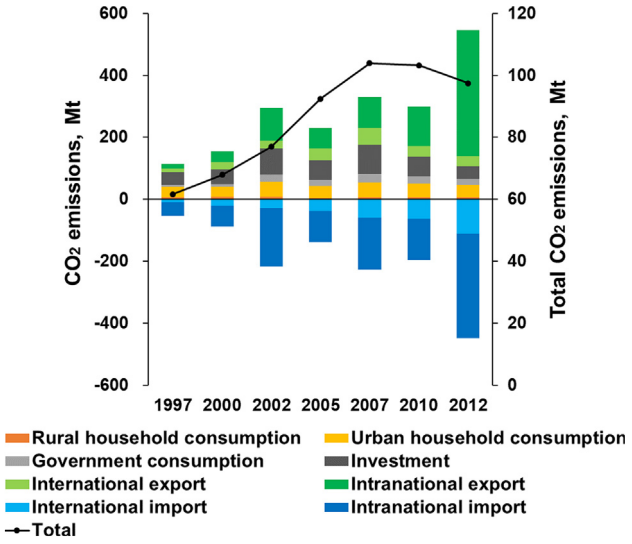

Fig. 4. CO_2 emissions from different final demand categories in Beijing, 1997–2012.

emissions, the turning point of which occurred in 2007. Specifically, during 1997–2007, 52.2% (22.1 Mt) and 30.6% (13 Mt) of the CO_2 emissions increment were caused by government consumption and urban household consumption, respectively. During 2007–2012, the total CO_2 emissions related to the final demand decrease were partly due to CO_2 emissions reduction in urban consumption (5.9 Mt) and government consumption (8.6 Mt).

3.2.3. Analysis from the perspective of socioeconomic driving factors

Fig. 5 presents cumulative changes in CO_2 emissions due to different driving factors. Energy intensity improvement was the most critical factor in curbing CO_2 emissions growth, and the significant emissions reduction associated with energy intensity improvement after 2007 is the determining factor for the emergence of the emission peak. Meanwhile, the relatively slight increase caused by changes in the production structure, which is the dominant factor leading to the growth of CO_2 emissions, also contributed to the turning point in 2007. Specifically,

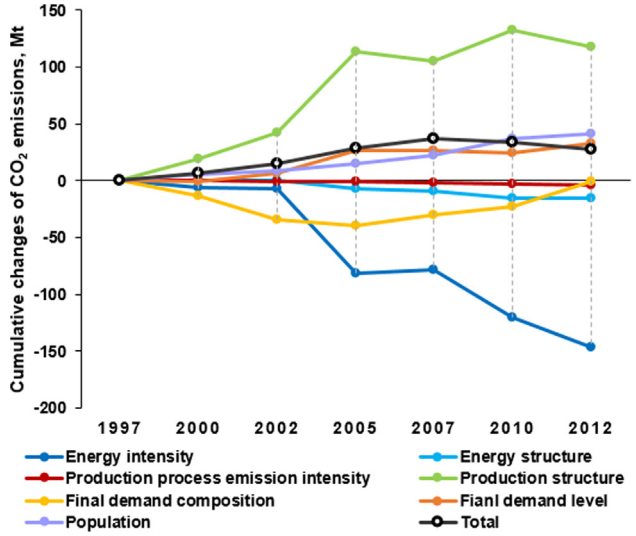

Fig. 5. Contributions from different driving factors on CO_2 emissions variation in Beijing, 1997–2012.

during the study period, mitigation of CO_2 emissions caused by energy intensity improvement was 146.1 Mt, and this reduction effect occurred in two significant stages: 2002–2005 and 2007–2012, accounting for shares of 50.5% (73.8 Mt) and 46.8% (68.4 Mt) of the total CO_2 emissions reductions related to energy intensity, respectively, during the whole period.

Changes in the production structure increased CO_2 emissions by 118.1 Mt from 1997 to 2012, which represents a fourfold increase over the total increase (27.8 Mt). The increase in CO_2 emissions due to production structure changes was dramatic during 2002–2005, accounting for 60.8% of the increment related to changes in the production structure during the entire period. Since 2005, CO_2 emissions associated with production structure changes fluctuated, and in fact, there were two rebounds during the periods 2005–2007 (8.1Mt decrease) and 2010–2012 (14.5 Mt decrease).

Unlike the notable effects of energy intensity improvements and production structure changes on CO_2 emissions variation, the influence of the energy structure changes on CO_2 emissions mitigation was weaker, but also cannot be ignored, considering its gradually increasing trend. In addition, with the increasing population rushing into Beijing, the cumulative impact of population growth on the increase of CO_2 emissions is gradually apparent, which accounted for 150.7% (41.8 Mt) of CO_2 increment during 1997–2012. The increase in final demand level also caused increases in CO_2 emissions, accounting for 118.2% (32.8 Mt) of CO_2 increment from 1997 to 2012.

3.3. Effects of in-depth industrialization process on CO_2 emissions

The industrialization process, a major component of the in-depth socioeconomic transition, has accelerated in recent years, influencing the CO_2 emissions peak of Beijing significantly. We investigated this influence from the following four aspects.

Fig. 6a represents the overall CO_2 emissions structure. Almost all of the CO_2 emissions were concentrated in three sectors, namely, construction, consumer service, and producer service. However, the volume of CO_2 emissions generated by these three sectors showed an overall downward trend from 2007 to 2012. That is, the mitigation of CO_2 emissions in the pillar industries in Beijing's economic structure was the major reason why the CO_2 emissions stopped growing since 2007. Specifically, during the 2007–2012 period, 312.6% (29.8 Mt), 207.6% (19.8 Mt), and 127.3% (12.1 Mt) of CO_2 emissions reduction were associated with consumer service, construction, and producer service, respectively. In addition, resources related heavy manufacturing played a significant role in avoiding CO_2 emissions, especially in the 2007–2012 period, accounting for 97 Mt CO_2 emissions reduction during this period, which was due to the outsourcing and transferring of resources related to heavy manufacturing in recent years.

Fig. 6b depicts the CO_2 emissions structure associated with export and import, which indicates the competitive or not effectively competitive industries of the economy. Considering the trade deficit, the CO_2 emissions were due to net-imports, which showed a steady decrease after 2007. With respect to resource-related heavy manufacturing and strategic emerging manufacturing, the two major sectors influencing the CO_2 emissions related to both export and import, a notable result was that both of them showed similarly high shares in the CO_2 emissions structure related to exports, as they were related to imports. This can be attributed to headquarters, such as Sinopec, impacting Beijing's intermediary trade. In total, these two industrial sectors helped avoid 173.2 Mt and 97.2 Mt CO_2 emissions, respectively, during the study period. The producer and consumer services were important sectors in the exports, while their shares in the imports were comparatively lower, because of services being a competitive industry in the economy structure.

Fig. 6c shows the structure of investment related CO_2 emissions excluding construction, which reveals industrial demand in the economic structure. Before 2007, strategic emerging manufacturing was the top contributor to CO_2 emissions related to investment, while after 2007, consumer service became the most important industry in terms of CO_2 emissions related to investment. In detail, the share of strategic emerging manufacturing decreased from 56.5% to 22.9% and resources related heavy manufacturing dropped from 18.5% to 7.7% during 1997–2012. However, both share and volume of the CO_2 emissions related to consumer service showed continuous growth from 2.3% (0.5 Mt) in 1997 to 59.9% (18.8 Mt) in 2010, Although its volume decreased from 18.8 to 8.2 Mt during 2010–2012, CO_2 emissions related to consumer service still occupied a large share of 58%. The results above can be attributed to the transition in the industry structure from manufacturing to services.

Fig. 6d shows the variation in CO_2 emissions caused by changes in the production structure, which reflect changes in the internal input structure by depicting the relationship between one sector and its upstream sectors. The top two influential sectors were the producer and consumer services sectors, occupying shares of 46.2% and 44.5%, respectively, of the CO_2 emissions increment related to the production structure during 1997–2010. It is noteworthy that there is a sharp rise in the CO_2 emission changes caused by producer and consumer services during 2002–2005, increasing by 221.4% and 275.9%, respectively. This explains why the production structure related to CO_2 emissions increased significantly during 2002–2005 as mentioned above. In the final two years of the study period, from 2010 to 2012, the producer and consumer services played positive roles in reducing CO_2 emissions, accounting for 48.4% (8.1Mt) and 63.4% (10.6 Mt) of production structure-related CO_2 emissions mitigation, respectively, which may be a consequence of upgrading the input structure of services in recent years. Construction, as the third important sector in the production structure-related emissions structure, showed a similar trend with producer and consumer services. It contributed to 24.1% (32Mt) of the CO_2 emissions increment during 1997–2010, and 34.5% (5.7 Mt) of the CO_2 emissions mitigation during 2010–2012.

3.4. Effects of in-depth urbanization process on CO_2 emission

The urban consumption-related CO_2 emissions exhibited a gradually declining trend after 2007, which decreased by 10 Mt during 2007–2012 (see Fig. 7a). Shelter and household equipment, services, and food and drink were the top three contributors to CO_2 emissions related to urban household consumption. Except for one year in 2005, shelter and household equipment was the largest source of CO_2

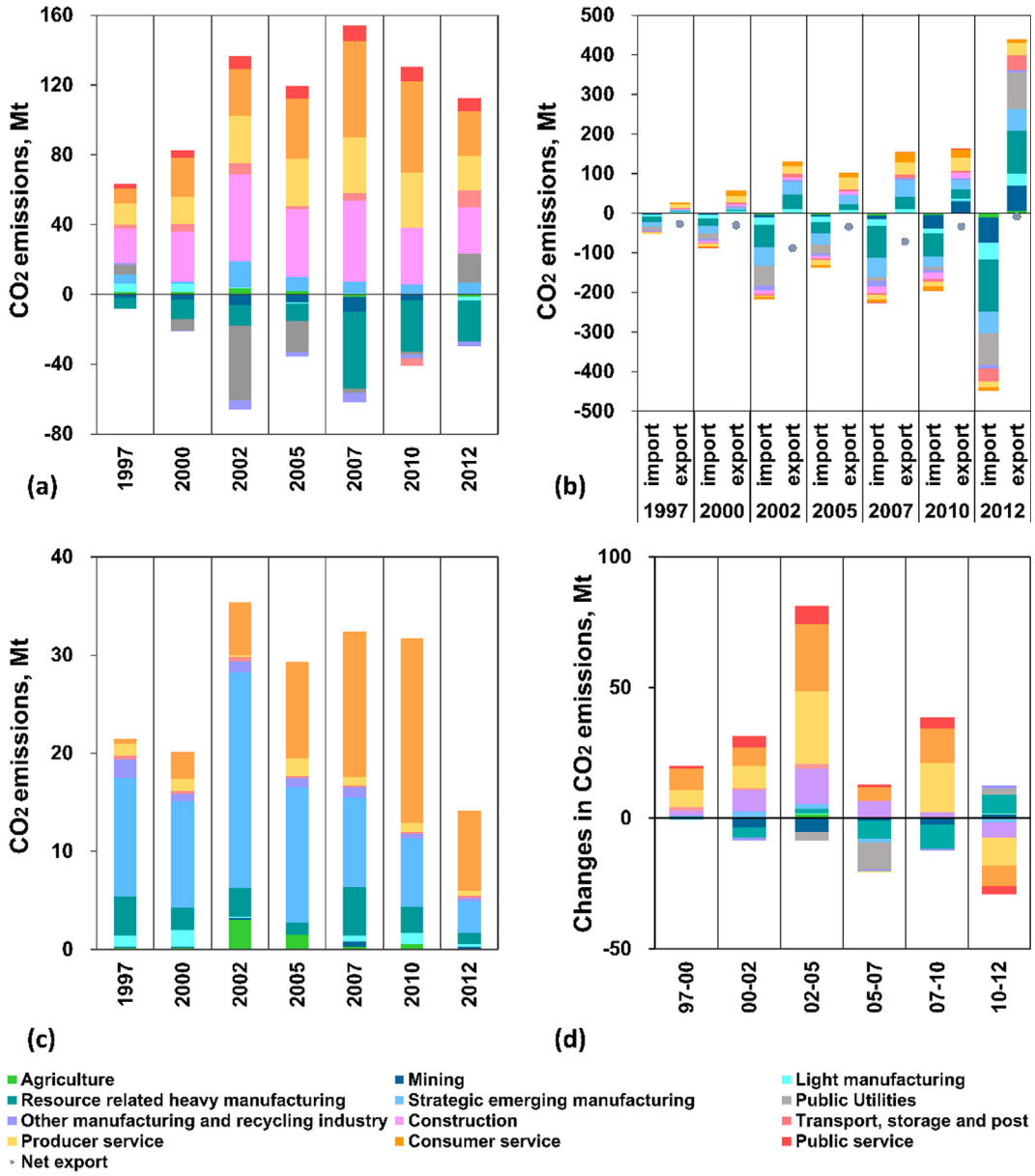

Fig. 6. Impacts of industrialization on CO_2 emissions in Beijing, 1997–2012; (a) overall structure of CO_2 emissions; (b) structure of import/export related CO_2 emissions, (c) structure of investment related CO_2 emissions, excluding construction; and (d) structure of CO_2 emissions related to changes in the production structure.

emissions, with its share varying from 42.5% to 59.2%. After 2007, shelter and household equipment related CO_2 emissions decreased (6 Mt) gradually. The services sector was the second major contributor and its CO_2 emissions increased during 1997–2005 with an annual growth rate of 7.7%, and then there was a continuous decline between 2005 (10.6 Mt) and 2012 (6 Mt). Food and drink, as the third major source of urban household consumption, showed a similar trend to shelter and household equipment, accounting for 1.4 Mt emissions mitigation during 2007–2012.

As for the per capita CO_2 emissions related to urban household consumption (see Fig. 7b), we found similar results. During 2007–2012, CO_2 emissions per capita decreased at the average annual rate of 7.5%, accounting for 1.1 t reduction. Services declined at the average annual rate of 13%, and CO_2 emissions per capita were reduced by 0.4 t during 2007–2012. The same results were observed for food and drink, and shelter and household equipment, which all declined slightly after 2007 at average annual rates of 8.4% and 7%, respectively.

From the viewpoint of the driving factors behind the CO_2 emission changes related to urban household consumption, compared with those behind the total CO_2 emissions, the production structure changes showed a similar trend. It also caused an increase in CO_2 emissions, though its influence was weaker (see Fig. 8). The important indicators of urbanization level, namely, population, urban household level, and urbanization rate, all increased CO_2 emissions with different degrees during the study period. Among these indicators, population was the most prominent, and the trajectory of CO_2 emissions changes related to population kept rising steadily, causing an 18.4 Mt emissions increment during the study period. The urban consumption level was the second major source of the CO_2 emissions increment during 1997–2012, leading to a 3.8 Mt increase in CO_2 emissions. The urbanization rate increased continuously, causing a 4.6 Mt increase in CO_2 emissions in the studied period. In terms of the driving factors mitigating CO_2 emissions, the intensity of CO_2 emissions played the sole significant role, accounting for 78.5 Mt of CO_2 emissions reduction during 1997–2015. Its impacts were particularly obvious during 2002–2005 and 2007–2012, leading to a sharp decrease in CO_2 emissions.

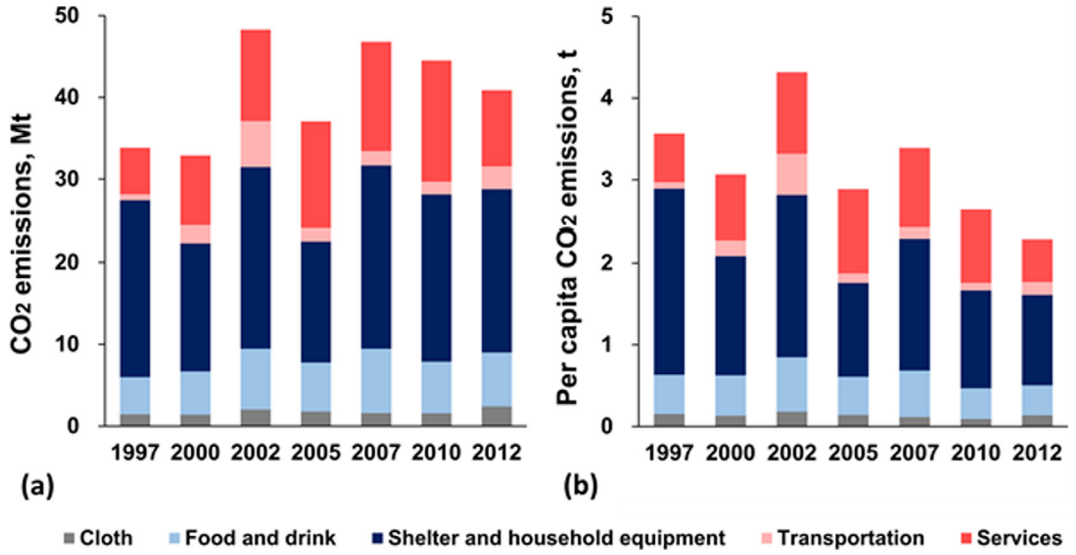

Fig. 7. Structure of CO_2 emissions related to urban household consumption: (a) total CO_2 emissions related to urban household consumption; and (b) per capita CO_2 emissions related to urban household consumption.

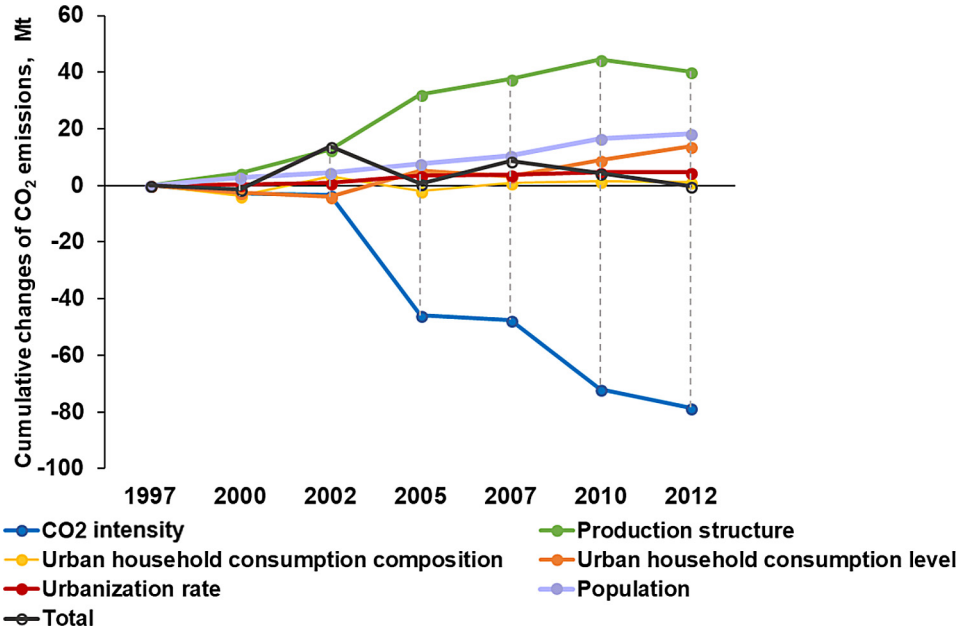

Fig. 8. Contribution of different factors driving variation in CO_2 emissions related to urban household consumption in Beijing, 1997–2012.

From the perspective of driving factors of CO_2 emission related to urban household consumption in major sources including services, shelter and household equipment, and food and drink, which all showed a continuous decrease after 2007, urban household consumption composition and CO_2 intensity were the main factors of CO_2 emissions reduction in services, during 2007–2012 (see Fig. A4 in the Appendix). Meanwhile, the change in the production structure curbed CO_2 emissions growth during 2010–2012. As for food and drink, and shelter and household equipment, apart from the CO_2 intensity, changes in the production structure also promoted CO_2 emission mitigation in shelter and equipment and in food and drink during 2010–2012.

4. Discussion

4.1. Impacts of in-depth socioeconomic transition on stagnating CO_2 emissions in Beijing

Production-based CO_2 emissions in Beijing stopped growing in recent years after experiencing a period of rapid increase. During this period, the in-depth socioeconomic transition in Beijing impacted its CO_2 emissions, stopping growth significantly.

The in-depth industrial transformation, as the major component of in-depth socioeconomic transition, influenced the CO_2 emissions peak significantly through the profound industrial structure change and technology improvement of sectors. For the case of industrial sectors, its share declined continuously due to the transition of economic gravity from industries to services in the past few decades. During the 12th Five-year Plan (FYP) period, the elimination of carbon intensive and energy intensive industries, such as resource-related heavy

manufacturing, was accelerated [49]. These explained why the CO_2 emissions in heavy manufacturing, as the major sources of CO_2 emissions in industrial sectors, showed a continuous decrease in recent years. Meanwhile, carbon intensive production processes were phased-out and traditional production techniques were gradually replaced by new emerging techniques in recent years [50], which optimized the production structure significantly. Therefore, CO_2 emissions related to changes in the production structure reduced in industrial sectors.

The services sector is another important contributor of peaking CO_2 emissions. In the period of the 11th [51] and 12th FYPs [52], Beijing proposed improvements in professional producer services including financial, information, technology, commercial, and distribution services. By the end of 2015, the internal structure transition of services featured as the producer service driven by innovation and technology realizing that the dominated role in the entire services was put forward [53]. Meanwhile, Beijing guided the development of newly-emerging consumer services and promoted better quality of consumer services through the improvement of technology [54]. Owing to technological upgrades, the elimination of the high-emissions production process was accelerated [55], which was the major reason for the adjustment of the production structure. As a benefit emanating from the changes in production structure, producer and consumer services all showed declining trends in recent years. In addition, improvement of technology levels, as the most leading factor for the decline in energy intensity [56], also significantly improved energy efficiency, which was the largest driving factor of the mitigation of emissions in services.

Apart from in-depth industrialization transition, in-depth urbanization process in Beijing also realized the stagnation of CO_2 emissions. Specifically, due to increasing residents' income with the improvement of urbanization levels, consumption patterns have become more diversified. From the consumption scale, rising incomes inevitably led to urban dwellers exhibiting high energy consuming features such as buying more food and clothes, using more household appliances, owning private transport, and so on (see A7 in the Appendix) [57], which potentially generated considerate emissions. In addition, for a better life, consumers pay a lot of attention to the quality of consumption, which caused the upgradation and optimization of urban household consumption composition, especially in the services, which became one of the important factors in CO_2 mitigation in the services sectors. Meanwhile, the upgradation of technology promoted the adjustment of production structure, and a decline in the intensity of CO_2 emissions, which were the major driving factors of CO_2 reduction in the services, shelter and household equipment, and food and drink. Due to the effect of changes in consumption composition and technology surpassing the effect of increasing consumption scale, CO_2 emissions related to urban household consumption reduced in the recent years. Furthermore, Beijing implemented many measures on population growth in most recent years, which led to slower growth rate [25]. Therefore, the effects of population growth on the increase in CO_2 emissions related to urban household consumption have been weakening since 2010.

Additionally, the occurrence of significant events in Beijing accelerated its socioeconomic transition, which promoted the arrival of the turning point from rapid growth to cessation of growth. Beijing held the Olympic Games in 2008. For the purpose of ensuring environmental quality, Beijing took many measures such as upgrading technologies of emissions reduction, during which the period of CO_2 emissions toward the peak started [58]. Furthermore, severe smog pollution events occurred frequently in recent years. Therefore, many measures on air pollution control were taken. All functions of the city unrelated to its status as the national capital city were divested. This functional dispersal further promoted the transition of the industry structure. Meanwhile, Beijing pressed forward with energy reforms in recent years, which significantly improved energy intensity and optimized the energy structure, all of which accelerated the CO_2 emissions peak.

4.2. Experience for peaking CO_2 emissions in Beijing

Considering the great disparities in socioeconomic development stages between different regions, Beijing's industrialization and urbanization processes with high-speed and in-depth traits cannot be replicated in other regions. However, its experience in CO_2 mitigation can still provide valuable guidance for other countries and regions worldwide, especially developing countries, which are also undergoing rapid socioeconomic transitions.

Firstly, technological improvement and transition of the internal structure of the industries require attention. Beijing stagnated its CO_2 emissions by promoting the improvement of production technology to realize the upgradation of industries and services. In some developed regions with high potential for CO_2 mitigation in services, they should focus on the growth of technology level, which can help optimize production structure and improve energy efficiency. Then, these factors further promoted mitigation. In some regions, the secondary industry, even the primary industry, still plays a significant role in their economic structure. Under such circumstances, it is necessary to focus on the elimination of carbon intensive production processes through the improvement of production techniques, and they can realize the emissions peak through technology mitigation.

Secondly, CO_2 attributable to urban household consumption should also receive more attention, especially for those regions in relatively early stages of urbanization. Increasing consumption demand and diversified consumption patterns have played negative roles in mitigating CO_2 emissions. The government needs to take some actions to improve saving consciousness of residents and promoting consumption composition upgradation. Meanwhile, these regions can implement some measures on population growth, which can help mitigate CO_2 emissions related to household consumption.

Thirdly, Beijing took effective actions to promote the transition of the industrial structure and adjustment of energy structures, which were key factors of the CO_2 emissions peak. Under the pressure of air pollution, multiple policies such as dispersal of function and energy reform were implemented, which had co-benefits on the CO_2 emissions peak. Relying on the powerful execution and management ability of the government, intensive policies were promulgated, which showed more obvious effects on promoting the transition of the economic structure compared to non-administrative measures. Under such circumstances, CO_2 emissions reduction in Beijing were accelerated. Other countries or regions can also fully utilize the high efficiency of governmental management and execution in achieving peaking CO_2 emissions.

4.3. Challenges of peaking CO_2 emissions based on the analysis of Beijing

Though the signs of peaking production-based emissions have been observed in Beijing, it is still uncertain when the turning point from ceasing growth to achieving meaningful decline will occur. There is even a possibility of a rebound in CO_2 emissions due to the increasing demand. Realizing CO_2 emissions peak will face many challenges in the future.

Firstly, there will be less potential for CO_2 mitigation through transition from industries to services considering the large share occupied by services in the economic structure. Additionally, the demand for services is increasing progressively and the comprehensive development of services is based on raw materials, and machinery and equipment, produced by primary and secondary sectors, respectively [59]. Services have become the biggest contributor of CO_2 emissions. How to further realize the low-carbon development of services through technology improvement and upgradation and internal structure adjustment becomes a major challenge of peaking CO_2 emissions.

Secondly, with the rapid urbanization process, both consumer demand and levels have risen continuously, and consumption patterns are becoming more diversified as residents seek a better and higher quality of life. An increasing number of products, transport, and services were

generated to meet the increasing demand, causing extensive CO_2 emissions. Hence, promoting the CO_2 emissions peak while fulfilling the great demand in the process of urbanization, is a major challenge.

Thirdly, although importing carbon intensive products and outsourcing resource-related heavy manufacturing were beneficial to the mitigation of Beijing's CO_2 emissions, the outcome at the global or national level remains to be discussed. The disparities in CO_2 emissions related to trading between different regions or countries will present a significant challenge in the nationwide peaking CO_2 emissions.

Lastly, though our research has confirmed that the production-based emissions in Beijing had showed the signs of peak in recent years, whether consumption-based emissions presented the trend of peak or not is still uncertain, which is also a limitation of this study. Due to the lack of high quality data, we do not compile time-series consumption-based emissions here. It is valuable to explore the trend and peak of emissions based on consumption further in future work. This will help us understand the challenge of peak better.

5. Conclusions

In this study, we investigated Beijing's CO_2 emissions trends with three scopes during 1997–2015 and analyzed the effects of in-depth socioeconomic transition on peaking CO_2 emissions. The results show that the turning point of Beijing's production-based CO_2 emissions from rapid increase to stopping growth was achieved in 2007, after which the emissions fluctuated around 100 Mt. However, the consumption-based CO_2 emissions still exhibited continuous growth during 1997–2012. From the perspective of the in-depth industrialization process, accelerating the elimination of energy and carbon intensive industries, such as resource-related heavy manufacturing, promoting the transition from industries to services, and upgrading internal structure within industries were key factors of the CO_2 emissions peak. Meanwhile, with technological improvements, the internal production structure of producer and consumer services was optimized, which caused a declining trend in CO_2 emissions in the services sectors. From the perspective of the in-depth urbanization process, the CO_2 intensity and production structure were improved further, which was the major reason for the reduction in CO_2 emissions related to the shelter and equipment sector in recent years. Meanwhile, upgraded services dominated that the consumption structure also promoted CO_2 mitigation related to urban household consumption.

Through our research on Beijing's journey toward the CO_2 emissions peak with in-depth socioeconomic transition, the challenges of CO_2 emissions peak in developing countries can be better understood. Meanwhile, the experience of emissions mitigation from Beijing can be provided. Specifically, curbing the increasing CO_2 emissions in services under the condition of its rapid development will be an important challenge. Beijing's experiences, such as upgrading the internal structure of industries, optimizing household consumption structure, and reinforcing the implementation of policies will be a valuable guidance on CO_2 emissions peak for other countries and regions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2018.07.029.

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